Nearshore Navigation and Communication Based on Deliberate EM Signals

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LONG-TERM GOALS

We seek to understand and utilize environmental and deliberately produced electromagnetic (EM) signals in the coastal ocean. Our studies are undertaken to provide a means for communicating with and guiding autonomous underwater vehicle (AUV) and other autonomous sensor systems, such as moored instruments. We include various EM influences in our models such as environmental noise , seabed electrical conductivity, variable bottom depth and coastline, and deliberate EM signals. The ultimate goal is to understand these factors well enough to reliably estimate signal-to-noise ratios in planning coastal EM operations and to improve basic understanding of EM propagation and environmental noise in the coastal waters.

OBJECTIVES

The immediate objectives are to study the fundamental generation and propagation of EM fields in realistic shallow coastal environments having non-uniform, three-dimensional geometries and to examine various sources of environmental noise expected for such regions. The environmental EM noise includes fields generated by external sources in the ionosphere and magnetosphere, by the dynamo action of the ocean flow, and by artificial sources, such as from the 50/60 Hz power grids.

APPROACH

The approach in this study has been to combine theory with numerical modeling. A primary element has been the development of a frequency-domain, finite difference/volume numerical model capable of calculating the generation and propagation of EM fields due to arbitrary sources in the presence of the strong land/air/sea conductivity contrasts and complicated 3D geometry of the realistic coastal ocean and land/sea/air environment.

Rather than use the standard Maxwell equations, a formulation in terms of electromagnetic gauge potentials is used from which the electric and magnetic fields are calculated in post-processing. Gauge potentials have been successfully exploited in numerical models with applications ranging from scattering problems (in which the EM fields are wavelike, e.g. Biro and Preis, 1989) to low-frequency geophysical induction problems (in which the process is diffusive, e.g. Badea et al. , 2001). Advantages of the gauge formulation for our applications are that it can be written in a way such that the potentials are everywhere continuous, it can be discretized on finite difference grids similar to those used by the ocean modeling community, gradients of conductivity (rather than resistivity) are used, and it allows arbitrary (including static) sources. Although it is a frequency-domain model it can be used to calculate the EM fields generated by arbitrary time-dependendent ocean flow on the continental shelves as the associated EM fields are essentially in static adjustment.

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14. ABSTRACT
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We have called the model MOED (Model for Ocean Electrodynamics) as its primary intended use is in calculating the generation and propagation of low-frequency (< 1 kHz) EM fields in or near the ocean. But as displacement currents have been included at little extra cost (and for stability considerations) it is equally capable of tackling more general high-frequency cases.

WORK COMPLETED

The primary accomplishment over the last year has been the improvement, completion, and validation of MOED and its use in several applications. The model has been developed by R. Tyler with programming assitance form F. Vivier. Some specific items follow.

We have combined several different previous versions of the model optimized for particular cases into one versatile model with appropriate switch-controlled options. For example, we have modified the formerly regular (possibly non-uniform) grid to allow for general orthogonal curvilinear coordinates such that MOED can accept ocean model (e.g. SCRUM/ROMS) data on native curvilnear or spherical coordinate grids. This allows MOED to both calculate the ocean generated EM fields as well as to use the particular model configuration in calculations involving atmospheric or artificial sources such that a consistent EM data set is added to the ocean model one. MOED now has several switches which can be used to improve performance. MOED even in its fully versatile mode, allowing displacement and conduction currents and no limiting assumptions, is quite fast (a fully coupled simultaneous solution of all four gauge potentials with 50K gridpoints typically takes a minute on a 550 MHz PC) and the user does not need to consider these switches for many problems. But depending on the case, there are often approximations that are exceedingly valid and for very large problems the switches are used to greatly increase the performance. MOED has been rewritten for maximum modularity and user-friendliness. It is entirely interfaced by MATLAB and plotting routines are also included in the distribution.

MOED has been validated in a diverse variety of cases ranging from the most simple ones for which there is an analytical solution (e.g. Fig. 1) to complicated geometries with extremely high parameter contrasts in which case the results are inspected for correct behavior (e.g. Fig 2).

The second most important accomplishment (Tyler, 2001b) has been an extension of the current theory of oceanic motional induction focusing on the non-local electric currents which historically have been poorly understood. While the ocean generated EM fields locally associated with the flow are well described by the theory of Sanford (1971), the ocean flow also generates electric currents closing non-locally in horizontal planes. Understanding the latter process is important primarily because the non-local electric currents are responsible for the component of the ocean generated magnetic field reaching outside of the ocean and because offshore flows generate EM fields on the shelf through these non-local electric currents.

With E. Maier-Reimer we have successfully performed a Helmholtz decomposition of the flow-dependent forcing vectors responsible for non-local electric currents generated by ocean circulation. This decomposition allows us to identify the components of ocean circulation responsible for the generation of these non-local electric currents.

With the help of a student (E. Peery) we have organized a global set of intercomparable time series from historical coastal geomagnetic observatory records together with processing scripts. We will use this for estimating the electric currents in coastal waters generated by ionospheric, magnetospheric

and oceanic sources. We have also written software for automatically calculating the ocean electrical conductivity, main magnetic field, and sediment conductance using, respectively, ocean climatologies of salinity and temperature, the IGRF main field model, and the global sediment conductance data of M. Everett.

Aside from the submitted paper (Tyler, 2001a), two related papers (Tyler, 2001b, Tyler and Sanford 2001) were presented by Tyler at the MARELEC 2001 (Marine Electromagnetics) conference in Stockholm this July and appear in the proceedings. A paper treating the Schumann propagation described above and a manual for MOED are nearing completion following which results concerning the coastal effect described above will be written up.

RESULTS

Several results from the theoretical analysis of ocean generated non-local electric currents (Tyler, 2001a,b) have important significance here. The first concerns a rigorous constraint on the time scales for magnetic diffusion in the ocean, the longest time scale being expected for the non-local currents. At least because there is a vast reduction in computational expense when the EM fields are known to be in approximate static adjustment with the flow field, it is important to be able to consistently evaluate this approximation. This was done by casting the EM induction equation onto geopotential surface, including the flow constraints, and then performing scale analyses. By comparing the speed of information propagation for a dynamical class of flow with the speed of 'lateral' magnetic diffusion (which involves propagation along the air and seafloor interfaces), constraints on the 'instantaneousness' of the EM adjustment were obtained. In the terminology of magnetohydrodynamics, this amounts to deciding whether the process falls into either the magnetic diffusive or frozen flux regimes. As it turns out, no oceanic processes are clearly in the frozen flux regime, some processes like deep-water barotropic Rossby waves and tides straddle the separtrix of the two regimes, and (fortunately) all flow processes resolved in coastal ocean circulation models fall into the magnetic diffusive regime. The last result indicates that when calculating the EM fields generated by the flows of these models there is no benefit in not using the less expensive static EM formulation.

A second significant theoretical result is more subtle. It illuminates an intrinsic inefficiency in the generation of non-local electric currents by geostrophic flow. This results because the non-local currents depend on the gradient of the ratio of the Coriolis parameter and radial main magnetic field. As both are axis aligned dipole fields to first order the ratio is similarly constant and the gradient vanishes. This should mean that while offshore flows such as tides may lead to strong electric fields on the shelf, the effect of offshore geostrophic flows is secondary.

Concerning the development and use of MOED, we have the following results. The numerical implementation using gauge potentials appears for these applications to be an efficient, reliable, and versatile method for calculating the EM fields. Aside from validation studies, we have also used MOED in a variety of applications including oceanic, atmospheric, and artificial sources. It can be seen in past MARELEC abstracts, for example, that aside from conventional EM applications such as vessel detection there is a growing number of new or expanded applications including underwater navigation and communication, mine counter measures, and marine petroleum and methane hydrate exploration. A recurring uncertainty in these applications concerns the inadequate understanding of environmental EM fields in the coastal ocean. Most of our recent simulations with MOED have been directed at this topic.

We have simulated the return electric currents in the ocean associated with the Global Circuit and observe that while these currents are typically very weak, they become significant in certain straits where they are highly concentrated. Even in those cases, however, these currents are not of primary relevance to the work here as they are primarily depth-uniform DC currents.

We have also simulated the well known "coastal effect" involving the amplification and distortion of magnetotelluric currents due to the strong coastal conductivity contrast. Alongshore magnetotelluric currents tend to be amplified around peninsulas with an opposite effect near bays. On/offshore magnetotelluric currents, conversely, can be stronger in bays than around peninsulas. The basic well-known effect of these currents being concentrated in shallow water is also seen in our results.

We are currently preparing a paper on the propagation of atmospheric Schumann resonant EM fields into the coastal environment. While there is typically a dearth of appropriate observations with which to compare our model results, Soderberg's (1969) observations provides a useful data set. He made observations of the horizontal components of the electric field at various depths in the Sea of Cortez at a location about 12 km offshore where the water depth was about 310 m. Atmospheric EM fields propagating directly down from the sea surface should show a frequency-dependent exponential decay (similar to that seen in Fig. 1) consistent with theory. As Schumann resonances (the lowest frequencies are about 8 and 14 Hz) provide peaks in the energy spectra with undoubtable atmospheric sources it was useful to concentrate on these frequencies. The amplitudes indeed decayed according to theory over most of the water column but as the seafloor was approached the amplitudes increased. He interpreted (correctly, we think) this result as follows. Unlike the open ocean, atmospheric EM fields can propagate into the ocean both from the surface and also through the seafloor by entering the coastal lands and propagating under the sea while refracting back up into the ocean. Hence when this seafloor propagation path is viable the minimum energy level in the water column will not necessarily be at the seafloor but at an intermediate depth which depends on sediment conductivity and distance to shore. Using the observed 14-Hz energy minimum depth of about 240 m and the distance to shore (12 km), he inferred a bulk sediment conductivity of 0.76 mS/m. Applying a 14 Hz Schumann source in MOED while using this sediment conductivity value and a similar configuration, we calculate an energy minimum depth very similar to what he observed. With MOED, we have been able to support and extend his initial conjecture. We have included information about the importance of the orientation of the incident atmospheric fields as well as frequency-dependent effects.

IMPACT/APPLICATIONS

There is a need for non-acoustical means of navigating and controlling AUVs, communicating with autonomous instruments, and detecting submerged and buried objects in shallow water. In principle, the extremely low-frequency EM signals (<1 kHz) we are investigating can be used for these purposes. In practice, however, not enough is known to predict reliable signal-to-noise ratios for particular applications. This is both because the propagation paths in the coastal environment are themselves non-trivial and because the background environmental fields are not well understood. MOED can be immediately used to calculate the EM signals due to an arbitrary artificial source in a specified realistic configuration. Our current effort is primarily focused on using MOED to further our understanding of the environmental fields.

TRANSITIONS

MOED has been completed and at this writing a manual is being written and the model is being prepared for distribution. The model will be distributed to colleagues at the Coastal Systems Station, the Swedish Defense Establishment, as well as the University of Paris and other academic institutions. Other interested parties may contact R. Tyler (tyler@apl.washington.edu).

RELATED PROJECTS

We have a project with the NSF International Program supporting a continuing collaboration with the German Climate Computing Center/Max Planck Institute for Meteorology in Hamburg. This collaboration started with J. Oberhuber and involved adding subroutines to the OPYC ocean circulation model for the purpose of calculating the EM fields generated by large-scale ocean circulation and resulted in several publications (e.g. Tyler et al. 1997). Since Oberhuber's departure from the institute our collaboration has proceeded with E. Maier-Reimer with whom we have continued similar EM calculations using the HOPE ocean circulation model.

R. Tyler has recently received an award for related work from the NASA New Investigator Program. In this work we are using theory and numerical models to calculate the magnetic fields at land and satellite locations due to global ocean tides.

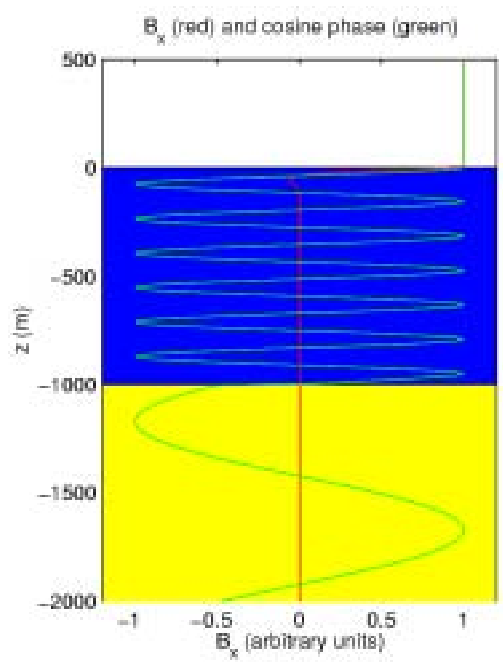

Figure 1: MOED solution for a 100-Hz horizontal magnetic field B_x (specified to have unit value at an altitude of 20 km) propagating down through the atmosphere (white), ocean (blue), and sediments (yellow). The model and theoretical solutions are essentially identical and show the exponential attenuation once the water is entered (real(B_x) in red) as well a the dependence of wavelength on conductivity (phase(B_x) is in green). For these parameters, theoretical skin depth is about 25 m and wavelength is about 160m. Conductivities used for air/sea/sediments were 4×10^{-13}/4/0.1 S/m.

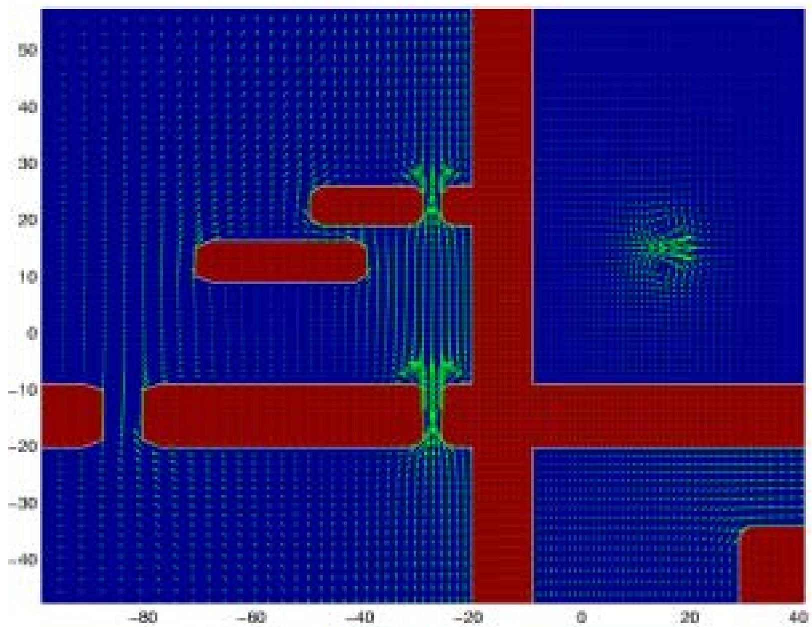

Figure 2: A 10-Hz dipole source in upper right seawater tank, couples inductively through insulating walls to neighboring tanks, two of which are coupled galvanically with channels. MOED simulations such as this are done to test for correct behavior and non-divergence in the vectors of electric current density (green) under complicated geometries and coupling scenarios. Vectors in the source tank are reduced for display.

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